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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
07/31/2009	Final Technical	12/30/2005 - 09/30/2009

4. TITLE AND SUBTITLE
A Generic Cerebellar-Based Controller for Dynamic State Estimation

5a. CONTRACT NUMBER
N/A

5b. GRANT NUMBER
N00014-06-1-0218

5c. PROGRAM ELEMENT NUMBER
N/A

6. AUTHOR(S)
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5d. PROJECT NUMBER
N/A

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
N/A

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 N Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
N/A

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited.

20100622201

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We aimed to produce a general method for controller development that requires minimal domain expertise and development time, yet outperforms traditional control methods. Our testbed system was a high degree-of-freedom 3-D biped robot. In simulation, we successfully demonstrated that surprisingly simple controllers can be evolved to exploit the passive dynamics of the robot and thus permit it to stand and to walk over rugged terrain (~6% leg length perturbations). A 'gray box' modeling approach is then used to integrate data gathered during walking trials on the actual (hardware) biped to adaptively improve the hardware model.

15. SUBJECT TERMS
Non-linear control, evolutionary robotics, bipedal locomotion, evolutionary algorithms, generalizable control algorithms, neural networks, limit cycle walking, passive dynamic walking, generalized control

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Mitra J Hartmann, PhD
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Scientific and Technical Objectives

Our objective has been to produce a general method for controller development that requires minimal domain expertise and development time, yet can outperform traditional control methods in several applications relevant to the Navy's strategic objectives. To demonstrate the utility of the approach, a high degree-of-freedom (DOF), three-dimensional (3D) biped has been incorporated as a testbed system.

Approach

The approach is to develop and refine algorithms in simulation, with an emphasis on the difficulties associated with transfer to hardware.

Approach 1: Our control algorithms are developed to ensure that they work in hardware, exploiting naturalistic locomotor movements and passive dynamics. This is a key difference between our work and previous research, which has focused almost exclusively on simulation results. We have constructed a nine DOF biped robot to test the ability of algorithms to overcome problems including sensor noise, actuator variability, parts wear, variable friction, time delays, nonlinear interaction forces, and difficult-to-model dynamics.

Approach 2: We test candidate control algorithms on reduced problems that permit us to quickly explore the effects of changing evolution operators and parameters. This ensures numerical tractability while exploring issues of scalability, computational speed, and adaptability to nonstationary dynamics. For this purpose, two-dimensional (2D) five-link and seven-link walking models have been developed.

Approach 3: We have developed complete dynamic simulations of the biped in the ADAMS and Open Dynamics Engine (ODE) physics simulation environments. Training the controller primarily in simulation as opposed to the actual robot permits the controller to learn from thousands of walking trials and reduces wear on the mechanical parts. A 'gray box' modeling approach is used to integrate data gathered during walking trials on the actual biped to adaptively improve the ODE model.

Concise Accomplishments

We have achieved the following during the current reporting period:

1. Completed coding and testing of a 2D, seven-link model (Figure 1). Significance: the seven-link model now incorporates feet, and hence the capability for ankle push-off and locomotion over rough terrain.

2. Implemented the neuroevolution algorithm on the 2D, seven-link model for stable walking over rough terrain (Figure 2). Significance: The controller framework is now fully developed and ready for implementation on a 3D walking model.

3. Implemented neuroevolution-based gait initiation and gait termination on the seven-link model. Significance: when applied to the robot, it should be able to start and stop autonomously, removing the need for difficult and unreliable human "launches."

4. Completed development of a 3D ODE simulation of the complete biped (Figure 3). Significance: The ODE simulation is necessary to train the final controller before transfer to hardware.

Expanded Accomplishments

In the past year, we have:

1. **Completed coding and testing of a 2D, seven-link model.** The model consists of an upper body, two thigh segments, two shin segments, and two feet. The terrain is simply modeled as a sequence of (x, y) points. Interpenetration constraints and joint-limits are enforced using soft constraints, and friction is modeled as traditional Coulomb friction. Coded in C++, the model runs extremely efficiently – about 40x faster than real time on an Intel Core 2 Duo T7300 laptop processor (including the control code). This speed is critical as it allows learning algorithms to be tested quickly on available hardware.

2. **Implemented the neuroevolution algorithm on the 2D, seven-link model for stable walking over rough terrain.** In moving from the five-link to the seven-link model, it was discovered that the non-discrete double-stance phase required implementation of a state machine for successful walking. The state machine consists of two possible states: 'push-off' and 'swing,' which is sent to the neurocontroller as a binary variable. In this framework, a critical part of learning to walk involves deciding whether the current state is 'push-off' or 'swing' – a decision that depends strongly on the nature of the local terrain, e.g. smooth downhill/uphill or abrupt step-down/step-up.

    The desired task for the seven-link model was stable and efficient locomotion over rough terrain. The terrain height varied each step with a standard deviation of 6% the biped's leg length (see Figure 1). The neuroevolution was run for 1000 generations 15 times, each run producing a stable and efficient controller. Upon the completion of each run, the final controller was tested for 100 "test walks," each lasting until 1000 Joules of energy are expended or the biped falls down. On the most successful run, the biped fell on only 5% of test walks (traveling an average of 67 meters, ~103x its leg length) and displaying a Specific Cost of Transport (a normalized measure of energy efficiency) of 0.142. By comparison, for humans walking on *level ground* this value is about 0.2, and for Honda's Asimo it is 3.23. A video of the resulting gait can be downloaded from here:
    http://www.mech.northwestern.edu/hartmann/Neuroevolved_Biped_Videos.html.

3. **Implemented neuroevolution-based gait initiation and gait termination on the seven-link model.** The limit cycle walking controller currently instantiated on the robot requires a human to manually "launch" (push) it into a stable limit cycle. This is unfavorable, due to both the obvious need for autonomous gait initiation for any useful bipedal robot, and the unreliability of the procedure for even an experienced human. To address this shortcoming, the above seven-link model experiments incorporated a gait initiation component with the locomotion controller, with the biped starting at rest and its legs side-by-side. The evolved controllers all displayed smooth and reliable gait initiation behavior, a video a where can be downloaded from here:
http://www.mech.northwestern.edu/hartmann/Neuroevolved_Biped_Videos.html
. In addition, a gait termination component was also easily evolved. Aside from the clear usefulness of gait initiation/termination, the straightforwardness with which the procedure was implemented indicates that the neuroevolution approach can also be extended to subsume additional locomotion capabilities, such as turning, walking sideways and backwards, avoiding obstacles and more.

4. **Completed development of a 3D ODE simulation of the complete biped.** Compared to the existing ADAMS model, it is geared more towards computational efficiency and low-level programmability.

Refereed Journal Articles

Status	Text
Published	Hobbelen DGE and Wisse M. Ankle actuation for Limit Cycle Walkers. *International Journal of Robotics Research*. 27(6), 709-735.
Submitted	Solomon JH and Hartmann MJZ. Braitenberg control for Limit Cycle Walking. *Biological Cybernetics*, under revision.

Non-Refereed Significant Publications

No non-refereed publications reported.

Books or Chapters

No books or chapters reported.

Technical Reports

No technical reports reported.

Workshops and Conferences

Invited Talk: Solomon JH and Hartmann MJH. Braitenberg control of a seven-link walking model. Dynamic Walking 2009, June 8-11, Vancouver, Canada.

Patents

No patents reported.

Awards/Honors

No awards/honors reported.